

FINAL REPORT

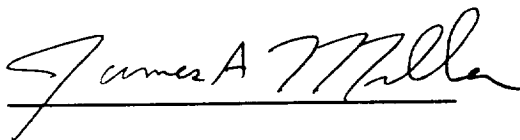
for

Ion Acceleration in Solar Flares

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Principal Investigator:

A handwritten signature in black ink, reading "James A. Miller", written over a horizontal line.

James A. Miller, Associate Professor
Department of Physics
The University of Alabama in Huntsville
Huntsville, AL 35899
Telephone: (256) 890-6276 Ext. 210
E-mail: miller@mpingo.uah.edu

Research Administrator:

A handwritten signature in black ink, reading "Sue B. Weir", written over a horizontal line.

Sue B. Weir
Office of Research Administration
The University of Alabama in Huntsville
Huntsville, AL 35899
Telephone: (256) 890-6000

1. Final Report

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Solar flares are among the most energetic and interesting phenomena in the solar system, releasing up to 10^{32} ergs of energy on timescales of several tens of seconds to several tens of minutes. Much of this energy is in the form of suprathermal electrons and ions, which remain trapped at the Sun and produce a wide variety of radiations, as well as escape into interplanetary space, where they can be directly observed. The radiation from trapped particles consists in general of (1) continuum emission, which ranges from radio and microwave wavelengths to soft (~ 1 – 20 keV) X-rays, hard (~ 20 – 300 keV) X-rays, and finally gamma rays (above ~ 300 keV), which may have energies in excess of 1 GeV; (2) narrow gamma-ray nuclear deexcitation lines between ≈ 4 and 8 MeV; and (3) high-energy neutrons observed in space or by ground-based neutron monitors. The particles that escape into space consist of both electrons and ions, which often have compositions quite different than that of the ambient solar atmosphere. Flares thus present many diagnostics of the particle acceleration mechanism(s), the identification of which is the ultimate goal of flare research. Moreover, flares in fact offer the only opportunity in astrophysics to study the simultaneous energization of both electrons and ions. Hopefully, an understanding of flares with their wealth of diagnostic data will lead to a better understanding of particle acceleration at other sites in the Universe.

Primarily as a result of the work of Reames and collaborators, it is now generally accepted that flares are roughly divided into two classes: impulsive and gradual. Gradual events are large, occur high in the corona, have long-duration soft and hard X-rays and gamma rays, are electron poor, are associated with Type II radio emission and coronal mass ejections (CMEs), and produce energetic ions with coronal abundance ratios. Impulsive events are more compact, occur lower in the corona, produce short-duration radiation, and exhibit dramatic abundance enhancements in the energetic ions. Their $^3\text{He}/^4\text{He}$ ratio is ~ 1 , which is a huge increase over the coronal value of about 5×10^{-4} , and they also possess smaller but still significant enhancements of Ne, Mg, Si, and Fe relative to ^4He , C, N, and O. Specifically, above about $1 \text{ MeV nucleon}^{-1}$, the ratio of Fe to O is about 8 times larger than in the corona or in gradual flares, while the ratio of Ne, Mg, and Si to O is about 3 times higher; ^4He , C, N, and O are not enhanced with respect to each other. In addition to these elemental enhancements, Ne and Mg have isotopic enhancements as well.

The general scenario that has emerged from these (and other) observations is that energetic particles in gradual events are accelerated by a CME-driven shock, while those particles in impulsive events are accelerated by another mechanism(s). *The goal of the research funded by this grant was to investigate a specific ion acceleration mechanism, and compare its predictions against the heavy ion abundance enhancement data.*

The basic idea is as follows: (1) During the primary flare energy release phase, when it is known that the magnetic field undergoes large-scale restructuring, we assume that large-wavelength low-amplitude MHD turbulence is formed (much like shaking a string will produce traveling waves). (2) Alfvén waves, which partially comprise this turbulence, will cascade to smaller wavelengths (higher frequencies). (3) As they cascade to higher frequencies, they will be able to gyroresonate and stochastically accelerate ions of progressively lower (eventually thermal) energy. Now, in a flare plasma, the waves will encounter

Fe first. Iron will be strongly accelerated but is not abundant enough to damp the waves. Thus, some wave energy will cascade to higher frequencies where it encounters Ne, Mg, and Si (the Ne group). The same way, these ions suffer strong acceleration but the wave dissipation is not complete. Some wave energy cascades to reach ^4He , C, N, and O (the He group). These ions are sufficiently numerous to totally damp the waves and the cascade ceases. Iron will resonate with the most powerful waves; the Ne group will resonate with waves having less power; and the He group will resonate with the least powerful waves. Hence, Fe should be enhanced more than the Ne group relative to the He group. Since ^4He , C, N, and O all have the same cyclotron frequency and behave similarly, they should not be enhanced relative to each other. This necessary layering of the cyclotron frequencies will occur in a plasma of temperature $\approx 3 \times 10^6$ K, which is the initial temperature argued for on this basis by Reames and coworkers. Hence, cascading Alfvén waves can qualitatively account for heavy ion enhancements.

With support from this grant, we first examined the feasibility of this idea by calculating in detail the damping rates from the various ions and the rate at which they absorb wave energy, and then comparing with the rate at which Alfvén wave energy will be flowing to higher frequencies. We found that, indeed, the above scenario of waves cascading through Fe, Ne, Mg, and Si will be realized for all reasonable flare conditions. We also applied these calculations to the recent “hot topic” of gamma-ray line emission from the Orion nebula, which implied the presence of energetic ions enriched in Fe. In this astrophysical setting, we found that cascading Alfvén wave turbulence accounted quite nicely for the properties of the accelerated ions, and produced a paper containing these results (“Abundance Enhancements in Black-Hole Accretion: Application to γ -ray Line Observations of the Orion Complex”, Miller, J. A., & Dermer, C. D. 1995, *Astron. Astrophys.*, **298**, L13).

With the theory semi-quantitatively grounded, we then constructed a quasilinear code to test the idea in detail. We assumed that the acceleration occurs in a single region, which consists of a uniform fully-ionized plasma permeated by a static homogeneous ambient magnetic field $\mathbf{B}_0 = B_0 \hat{\mathbf{z}}$. The four components of the plasma are Fe ions, Ne group (Ne, Mg, Si) ions, He (^4He , C, N, O) group ions, and electrons. The length of the region along the magnetic field is L . Particles escape from the region upon crossing a boundary either at $z = 0$ or $z = L$ (that is, we take the loss cone half angle to be 90° at both ends). We assume that a homogeneous spectrum of Alfvén waves exists throughout the acceleration region.

We assume for simplicity that the Alfvén waves propagate parallel and antiparallel to \mathbf{B}_0 . These waves have left-hand circular polarization relative to \mathbf{B}_0 and occupy the frequency range below the hydrogen cyclotron frequency Ω_H . The acceleration of each ion species was then described through a Fokker-Planck equation in energy space, taking into account transit escape losses through a leaky-box term having a characteristic escape time scale of $2L/v$.

The injection, cascading, and damping of the waves are described by a diffusion equation in wavenumber space

$$\frac{\partial W_T}{\partial t} = \frac{\partial}{\partial k_{\parallel}} \left(D_{\parallel\parallel} \frac{\partial W_T}{\partial k_{\parallel}} \right) - \gamma(k_{\parallel}) W_T + S,$$

where W_T is the spectral density, k_{\parallel} is the parallel wavenumber, $D_{\parallel\parallel}$ is a coefficient that depends upon W_T and can be determined for Kolmogorov cascading, $\gamma(k_{\parallel})$ is the damping rate due to accelerating ions, and S is the volumetric wave energy injection rate per unit k_{\parallel} . Since the spectral density is symmetric about $k_{\parallel} = 0$, we only consider $k_{\parallel} > 0$. Here $S = Q\delta(k_{\parallel} - k)$, where Q is the volumetric wave energy density injection rate Q at either k or $-k$. The total rate of wave energy injection in both parallel and antiparallel waves is therefore $2Q$.

The resulting system of 4 coupled, nonlinear, partial differential equations was solved numerically with implicit finite differencing. The ion spectra could then be easily integrated to obtain abundance ratios. We found (“Heavy Ion Acceleration by Cascading Alfvén Waves in Impulsive Solar Flares”, Miller, J. A., & Reames, D. V. 1996, in *High Energy Solar Physics*, eds. R. Ramaty, N. Mandzhavidze, & X.-M. Hua (New York: AIP), p. 450) that for a broad range of turbulence injection rates and acceleration region lengths, the heavy ion abundance ratios observed in impulsive solar flares could be readily reproduced. The model was therefore considered a success, and has provided an excellent argument in favor of stochastic acceleration as the acceleration mechanism that is operating in impulsive solar flares.

In addition to the above two papers, this grant also supported the work on a comprehensive invited review paper on particle acceleration in solar flares (“Critical Issues for Understanding Particle Acceleration in Impulsive Solar Flares”, Miller, J. A., Cargill, P. J., Emslie, A. G., Holman, G. D., Dennis, B. R., LaRosa, T. N., Winglee, R. M., Benka, S. G., & Tsuneta, S. 1997, *J. Geophys. Res.*, *102*, 14631). In this paper, we evaluated all of the proposed acceleration mechanisms in light of the observational data, and concluded that stochastic acceleration offers the best hope by far of explaining all of the properties of the energetic particles.